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Physics and applications of three-ion ICRF scenarios for fusion research

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ABSTRACT

This paper summarizes the physical principles behind the novel three-ion scenarios using radio frequency waves in the ion cyclotron range of frequencies (ICRF). We discuss how to transform mode conversion electron heating into a new flexible ICRF technique for ion cyclotron heating and fast-ion generation in multi-ion species plasmas. The theoretical section provides practical recipes for selecting the plasma composition to realize three-ion ICRF scenarios, including two equivalent possibilities for the choice of resonant absorbers that have been identified. The theoretical findings have been convincingly confirmed by the proof-of-principle experiments in mixed H–D plasmas on the Alcator C-Mod and JET tokamaks, using thermal ^{3}He and fast D ions from neutral beam injection as resonant absorbers. Since 2018, significant progress has been made on the ASDEX Upgrade and JET tokamaks in H–^{4}He and H–D plasmas, guided by the ITER needs. Furthermore, the scenario was also successfully applied in JET D–^{3}He plasmas as a technique to generate fusion-born alpha particles and study effects of fast ions on plasma confinement under ITER-relevant plasma heating conditions. Tuned for the central deposition of ICRF power in a small region in the plasma core of large devices such as JET, three-ion ICRF scenarios are efficient in generating large populations of passing fast ions and modifying the *q*-profile. Recent experimental and modeling developments have expanded the use of three-ion scenarios from dedicated ICRF studies to a flexible tool with a broad range of different applications in fusion research.

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I. INTRODUCTION

Strong magnetic fields are used to confine plasmas in fusion devices. As a result of the Lorentz force, plasma ions and electrons gyrate around the magnetic field lines with a local characteristic cyclotron frequency $\omega_{cs} = q_s B/m_s$, where q_s and m_s are the charge and the mass of the particle and B is the local value of the magnetic field. Note that ions rotate in the clockwise direction, while electrons rotate counter-clockwise, when viewed in the direction opposite to the magnetic field. For typical magnetic fields in present-day and future tokamaks, the ion cyclotron frequencies broadly cover the range between ∼10 MHz and ∼100 MHz. A system for plasma heating with waves in the ion cyclotron range of frequencies (ICRF) is under development for ITER, aiming to deliver 20 MW of heating power in the frequency range 40–55 MHz.[1–4] In addition to plasma heating, ICRF systems have a broad range of additional applications, as discussed in recent overviews.[5,6]

ICRF heating relies on the excitation of fast magnetosonic waves that can be absorbed by both ions and electrons via a large number of collisionless absorption mechanisms in the plasma.[7–10] A necessary condition for fundamental ion cyclotron ($n = 1$) and harmonic damping ($n = 2, 3, \ldots$) is the local match between the Doppler-shifted wave frequency and the ion cyclotron frequency or harmonics

$$\omega = n\omega_{ci} + k_{||}v_{||,i} (n = 1, 2, 3, \ldots). \tag{1}$$

Here, $\omega = 2\pi f$ with f being the frequency of the launched radio frequency (RF) waves; $k_{||}$ and $v_{||,i}$ are the wavenumber and ion velocity parallel to the confining magnetic field; and n is the cyclotron harmonic number. In turn, Eq. (1) determines the parallel velocities for resonant ions

$$v_{||,i} = (\omega - n\omega_{ci})/k_{||}. \tag{2}$$

For thermal ions with low $v_{||}$, this condition can be fulfilled close to the ion cyclotron resonance layers, where $\omega \approx n\omega_{ci}$. Note that the physics of ICRF heating is very rich and extends beyond ion cyclotron interactions only. In particular, fast waves can also be absorbed directly by electrons or undergo a transformation to shorter wavelength modes via mode conversion.[11,12]

The RF electric field of the propagating fast waves can be written as the sum of a left-hand, E_+ (rotating in the direction of the ions) and a right-hand, E_- (rotating in the direction of the electrons) polarized component.[13] Efficient ion cyclotron damping for thermal and moderately energetic ions occurs when Eq. (1) is satisfied in a region with a high $|E_+|$.[9] To a large extent, the plasma composition determines the spatial distribution of the ratio E_+/E_- in the plasma volume and thus is a crucial parameter to optimize the ICRF heating efficiency.

Out of all existing ICRF heating scenarios, minority heating is the most routinely used in fusion research. In its simplest version, this heating scenario is realized in two-ion species plasmas with different charge-to-mass ratios, where the concentration of one of the ion species (minority) is much lower than that of the other one. Minority ions absorb RF power close to their cyclotron resonance, $\omega \approx \omega_{ci,mino}$ ($n = 1$). In its purest form, minority heating is obtained at a negligible minority concentration that is low enough such that it does not affect the wave propagation characteristics.[7,8] In practice, minority heating is applied at higher minority concentrations, $X_{mino} = n_{mino}/n_e$ (here, n_{mino} is the minority density and n_e is the electron density), typically from a few % to ∼10%. This is not only due to a higher density of resonant ions, but also because of the appearance of the so-called ion–ion hybrid (IIH) layer.[14] The E_+ component is locally enhanced at this layer (see Sec. II), facilitating RF power absorption by minority ions.

The radial position of the IIH layer in the plasma depends on the plasma composition.[12] As the concentration of minority ions increases, the IIH layer shifts further away from the minority cyclotron resonance toward the cyclotron resonance of the other ion species. Eventually, the distance to the IIH layer gets too large for both plasma ion species and they can no longer resonate at the region with an enhanced $|E_+|$. Under these conditions, ICRF heating via mode conversion becomes dominant, where launched RF fast waves undergo a